

# Three zone equilibrium and kinetic free modeling of biomass gasifier – a novel approach

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## ABSTRACT

Two zone equilibrium and kinetic free model proposed by the authors in their earlier work [Ratnadhariya JK, Channiwala SA. Two zone equilibrium and kinetic free modeling of gasifier. Proceedings of the 12th European Conference and Technical Exhibition on Biomass for Energy, Industry and Climate Protection. Amsterdam, The Netherlands; 2002. p. 813–816], offers gas composition, temperature profile and gasifier performance parameters for two zones. This model does not predict composition and temperature profile of pyrolysis zone, which is stated to be a precursor for gasification. Looking to this fact a three zone equilibrium and kinetic free model of biomass gasifier is proposed in the present work. In this three zone: first zone of the model is drying and pyrolysis zone combined together; second zone is oxidation zone; and the third zone is the reduction zone. Each zone has been formulated with: (i) reaction stoichiometry; (ii) constituent balance; and (iii) energy balance along with a few justifying assumptions. This model clearly provides an operating range of equivalence ratio and moisture content for the woody biomass materials. Further, this model facilitates the prediction of the maximum temperature in the oxidation zone of gasifier, which provides useful information for the design of the gasifier and selection of the material for the construction. The merits of the model lies in the fact that it is capable of handling predictions for all category of biomass materials with a wide operating range of equivalence ratio and moisture content in all of the three principal zones of the gasifier.

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## 1. Introduction

A novel approach has recently been introduced by the authors to formulate a two zone equilibrium and kinetic free model of the gasifier based on a few justifying assumptions, which indirectly considers reaction kinetics through exothermicity and endothermicity of principal oxidation and reduction reactions [1]. The present model is an extension of the same effort.

The present model identifies the sequence of principal reactions and a degree of each reaction is considered to be inversely proportional to their exothermicity or endothermicity and hence does not need any assumptions about thermodynamic equilibrium. It predicts composition and temperature levels in three zones simply from mass and energy balances.

## 2. Physical description of model

Fig. 1 gives the overall view of the physical model of the downdraft gasifier along with possible reactions in the different

zones. Drying and pyrolysis zones are clubbed together. The products of pyrolysis zone, i.e., 1st zone are assumed to be char, CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> [2–8]. Higher hydrocarbons are not considered as they crack during secondary pyrolysis in the gasifier as observed by Antal et al. and others [5,9–12]. Similarly, many recent studies on pyrolysis gives gas composition at different temperatures and different heating rates and their results clearly indicate release of CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub> and tar with a higher concentration of lighter components [5–8,13].

The initial association of C, H and O with each other during formation of biomass [14–19] along with process parameters, i.e., temperature, rate of heating, etc., usually govern the product quality and yield in the pyrolysis zone [9–11,13,20,21]. Channiwala [14] has observed that the majority of HHV correlations are based upon the different assumptions regarding association of oxygen with hydrogen or carbon. Dulong [15] and Strache and Lant [16] have used the concept of available hydrogen and assumed fuel oxygen to be totally associated with hydrogen. Steuer [17] and Sumegi [18] have considered the association of fuel oxygen with both hydrogen and carbon while Vondracek [19] has assumed more availability of hydrogen. Sumegi [18] has assumed (3/8) O to be associated with C and (1/16) O to be associated with the hydrogen

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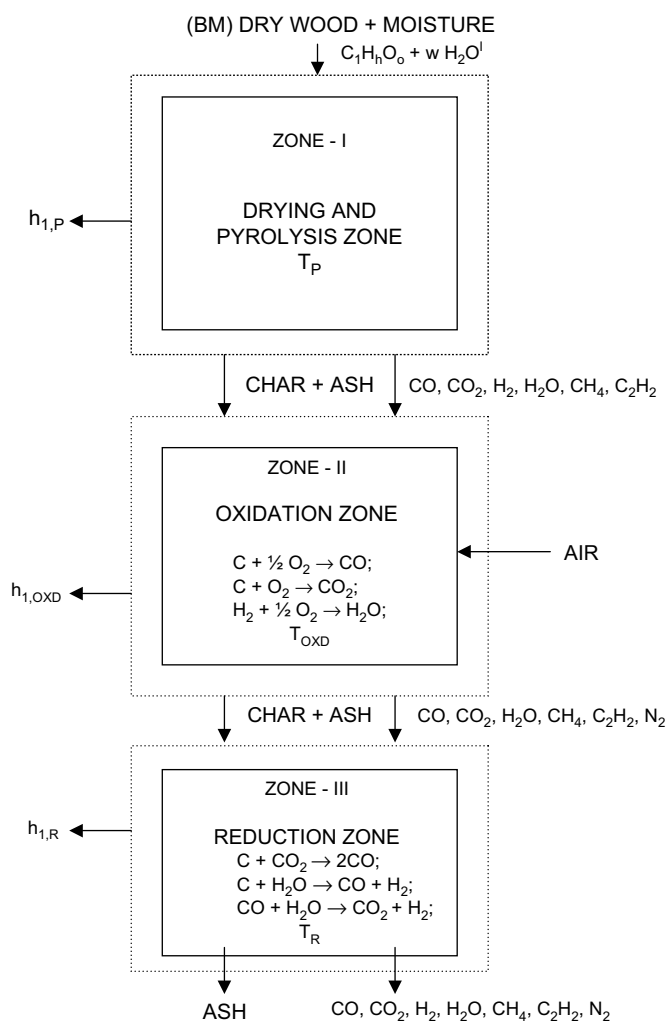


Fig. 1. Three zone equilibrium and kinetic free model of the downdraft gasifier.

while Mott and Spooner [22] has assumed (2/3) O to be associated with hydrogen and (1/3) O with C.

The association of fuel oxygen with carbon and hydrogen both seems to be logical if one studies both HHV predictions based on pure pertinent combustion reactions [14] and the devolatilization results [5,6,9,10,20,21,23]. In the present model of pyrolysis zone, based on these realizations and the fact that the affinity between H and O is much higher than that of C and O, it is assumed that 80% of fuel oxygen, i.e., (4/5) O is associated with fuel hydrogen in the form of  $H_2O$  while, 20% of fuel oxygen, i.e., (1/5) O is associated with fuel carbon on mole basis and releases as CO and  $CO_2$  on decomposition and the ratio of moles of CO and  $CO_2$  is assumed to be inversely related with their molecular mass [5–8,13]. Fifty percent of balanced hydrogen in fuel releases as  $H_2$  on decomposition [6,13] and the remaining 50% of balanced hydrogen in the fuel is released in the form of  $CH_4$  and  $C_2H_2$  and the ratio of moles of  $CH_4$  and  $C_2H_2$  is assumed to be inversely related with their molecular mass [5–8,13]. The gas composition and temperature in this zone is governed by mass and energy balance.

The product from the pyrolysis zone enters oxidation zone where incoming air reacts with these products and  $H_2$  is fully oxidized to  $H_2O$  [2,24–29]. Balanced oxygen will be consumed in char oxidation [2,3,27–31] due to a very high reactivity of char. The char oxidation yields CO and  $CO_2$ , which are assumed to be inversely proportional to the exothermicity ( $n_{CO}/n_{CO_2} = 3.5606$ ) of

their reactions [2,3,27–29]. Finally, CO and  $CO_2$  from the pyrolysis zone will be simply added up to the CO and  $CO_2$  produced by char oxidation.  $CH_4$  and  $C_2H_2$  are simply assumed to be carried forward from the pyrolysis zone to oxidation zone due to their lower burning velocities and oxygen deficiency [2,27–29]. Thus, the products of the oxidation zone are char, CO,  $CO_2$ ,  $H_2O$ ,  $CH_4$ ,  $C_2H_2$  and  $N_2$  [2–4]. The overall composition and temperature in this zone is obtained through mass and energy balance.

The products from the oxidation zone enter reduction zone. The possible products of the reduction zone are assumed to be CO,  $CO_2$ ,  $H_2$ ,  $H_2O$ ,  $CH_4$ ,  $C_2H_2$  and  $N_2$  [2,5–8]. The water–gas shift reaction is assumed to have a degree of reaction as a unity at the entry of reduction zone as it is a gas phase homogeneous reaction [2–4,32–37]. Char carry over is assumed to be zero [38,39].  $CH_4$ ,  $C_2H_2$  and  $N_2$  from the oxidation zone are carried forward to product gas [2,3,27–29,40]. Balanced carbon will be utilized by principal reduction reactions in inverse ratio of their endothermicity, i.e., Boudouard reaction will consume 43.22% carbon while water–gas reaction will consume 56.78% carbon [3,27–29]. The composition and temperature in this zone is obtained through mass and energy balance.

### 3. Model formulation and solution

The model formulated in this work consists of three constituent sub-models, one for each zone, i.e., pyrolysis, oxidation and reduction zone. The basic assumptions on which the overall model has been formulated are similar to two zone equilibrium and kinetic free model [1].

- (1) The char is modeled as graphitic carbon [2,38,39].
- (2) The process of gasification is isobaric [3,39,41].
- (3) Char carry over from the gasifier is taken as 0% on molar basis [38,39].
- (4) There is no heat transfer between the various zones [1,2].
- (5) The overall direct heat loss from the gasifier is assumed to be related to both the equivalence ratio and the HHV of biomass material [2]. Heat loss depends on temperature levels of gasifier. The temperature levels in gasifier are governed by equivalence ratio and HHV of biomass. For gasification process requiring oxygen deficient atmosphere, the reactor temperature increases with increasing equivalence ratio and HHV of feed material, therefore, the overall heat loss is assumed to be the product of equivalence ratio and HHV. For biomass having HHV in the range of 15–20 MJ/kg and operating in equivalence ratio range of 0.25–0.45, the overall heat loss will vary in the range of 3.0–6.0% [2,43]. Taking this into account the overall heat loss is assumed to be 10% of the product of equivalence ratio and HHV [2,41–43]. This loss is distributed in pyrolysis, oxidation and reduction zones based on the study of temperature profiles of gasifier by Bliet [43] and Channiwala [2] where the maximum temperature is observed at oxidation zone, slightly lower levels in the reduction zone and still lower levels in pyrolysis zone. Typical average temperature is in the order of 850, 650 and  $500^\circ C$  in oxidation, reduction and pyrolysis zone, respectively. Accordingly the heat losses in pyrolysis, oxidation and reduction zone are assumed to be 25, 40 and 35% of this loss, respectively [2].

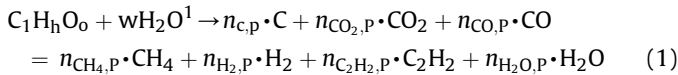
#### 3.1. Formulation of pyrolysis zone model

Assumptions:

- (1) 4/5 of the fuel oxygen is associated with fuel “h” in the form of  $H_2O$  [14–19,22].

- (2) 1/5 of the fuel oxygen is associated with fuel carbon and releases as CO and CO<sub>2</sub> on decomposition [14–19,22].
- (3) The ratio of moles of CO and CO<sub>2</sub> is inversely related with their molecular mass, i.e., CO/CO<sub>2</sub> = 44/28 [5–8,13].
- (4) 50% of available hydrogen in fuel releases as H<sub>2</sub> on decomposition [5,13].
- (5) Balanced 50% of available hydrogen in fuel is released in the form of CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> [5,13].
- (6) The ratio of moles of CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> is inversely related to with their molecular mass, i.e., CH<sub>4</sub>/C<sub>2</sub>H<sub>2</sub> = 26.016/16.032 [5–8,13].
- (7) The products of pyrolysis zone are C, CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> [2–8].

Reaction stoichiometry:



Constituent balance:

$$ttl_{C,P} = 1 = n_{C,P} + n_{CO,P} + n_{CO_2,P} + n_{CH_4,P} + 2n_{C_2H_2,P} \quad (2)$$

$$ttl_{H,P} = h + 2w = 2n_{H_2,P} + 2n_{H_2O,P} + 4n_{CH_4,P} + 2n_{C_2H_2,P} \quad (3)$$

$$ttl_{O,P} = o + w = n_{CO,P} + 2n_{CO_2,P} + n_{H_2O,P} \quad (4)$$

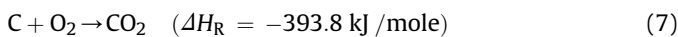
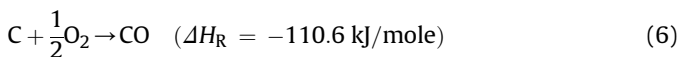
Energy balance:

$$\left[ h^0f + (h_{Tr} - h_{298}) \right]_{BM} + w[h^0f + (h_{Tr} - h_{298})]_{H_2O}^1 \\ = \sum n_{j,P} \left[ h^0f + (h_{T,P} - h_{298}) \right]_{j,P} + h_{1,P} \quad (5)$$

### 3.2. Formulation of oxidation zone model

Assumptions:

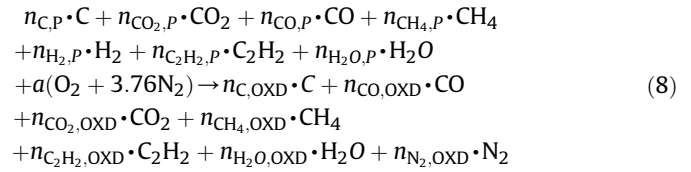
- (1) Hydrogen from the pyrolysis zone is fully oxidized to H<sub>2</sub>O due to its highest burning velocity [2,24–29].
- (2) The balance oxygen will be consumed in char oxidation due to much larger reaction area available for O<sub>2</sub> adsorption on highly reactive pyrolysis char [2,3,27–31].
- (3) CO, CO<sub>2</sub> distribution is considered to be inversely proportional to the exothermicity of their reactions, i.e., less exothermic reaction is assumed to be proceeding at a faster rate than higher one [2,3,27–29]. The principal char oxidation reactions considered are:



These reactions will proceed in the inverse ratio of their exothermicity, i.e.,  $n_{CO,O}/n_{CO_2,O} = 3.5606$ .

- (4) The CO and CO<sub>2</sub> from the pyrolysis zone is assumed to be simply added up to the CO and CO<sub>2</sub> produced by char oxidation.
- (5) CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> are assumed to be carried forward to reduction zone due to their low burning velocities and lack of oxygen [2,27–29].
- (6) The products of the oxidation zone are char, CO, CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> and N<sub>2</sub> [2–4].

Reaction stoichiometry:



Constituent balance:

$$ttl_{C,OXD} = n_{C,P} + n_{CO,P} + n_{CO_2,P} + n_{CH_4,P} + 2 \cdot n_{C_2H_2,P} \\ = n_{C,OXD} + n_{CO,OXD} + n_{CO_2,OXD} + n_{CH_4,OXD} + 2n_{C_2H_2,OXD} \quad (9)$$

$$ttl_{H,OXD} = 2n_{H_2,P} + 2n_{H_2O,P} + 4n_{CH_4,P} + 2 \cdot n_{C_2H_2,P} \\ = 2 \cdot n_{C_2H_2,OXD} + 4n_{CH_4,OXD} + 2n_{H_2O,OXD} \quad (10)$$

$$ttl_{O,OXD} = n_{CO,P} + 2n_{CO_2,P} + n_{H_2O,P} + 2a \\ = n_{CO,OXD} + 2n_{CO_2,OXD} + n_{H_2O,OXD} \quad (11)$$

$$ttl_{N,OXD} = (3.76 \cdot 2)a = 2n_{N_2,OXD} \quad (12)$$

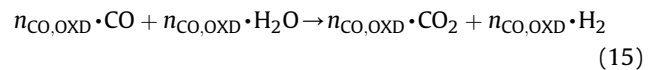
Energy balance:

$$\sum_k n_{K,P} \left[ h^0f + (h_{T,P} - h_{298}) \right]_{K,P} \\ = \sum_j n_{j,OXD} \left[ h^0f + (h_{T,OXD} - h_{298}) \right]_{j,OXD} + h_{1,OXD} \quad (13)$$

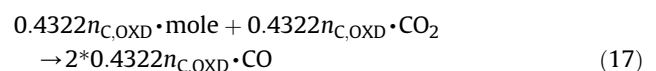
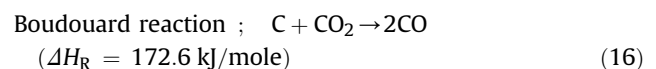
### 3.3. Formulation of reduction zone model

Assumptions:

- (1) The products of the reduction zone are assumed to be CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> and N<sub>2</sub> [2,5–8].
- (2) CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> from the oxidation zone are carried forward to product gas due to oxygen deficiency and consumption of char by reduction reactions [2,3,27–29,40].
- (3) The gas phase homogeneous shift reaction is assumed to have a degree of reaction as a unity at the entry of reduction zone [2–4,32–37].



- (4) The principal reduction reactions are Boudouard reaction and water–gas reaction. Both these heterogeneous reactions are assumed to consume char in the inverse ratio of their endothermicity [3,27–29]. This means that water–gas reaction proceeds faster than Boudouard reaction. A total of 43.22% of char from the oxidation zone is consumed by Boudouard reaction and 56.78% of char from the oxidation zone is consumed by water–gas reaction. Thus, both these reactions may be represented as:



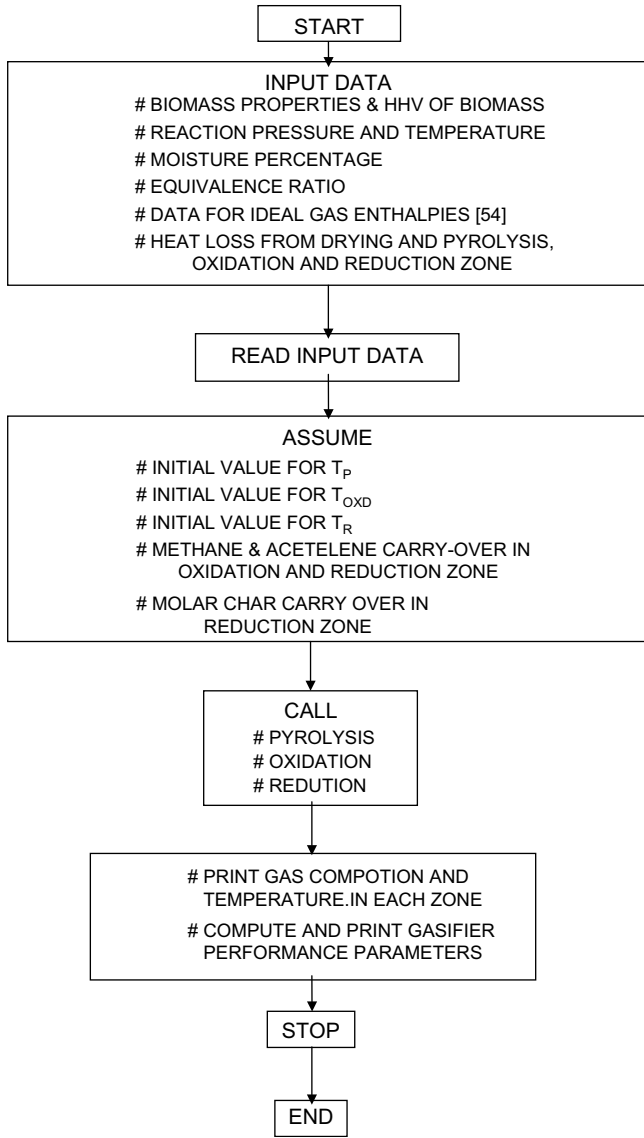
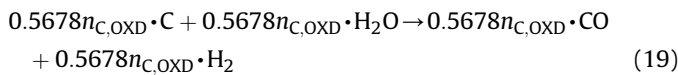
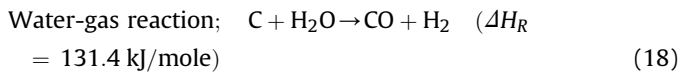
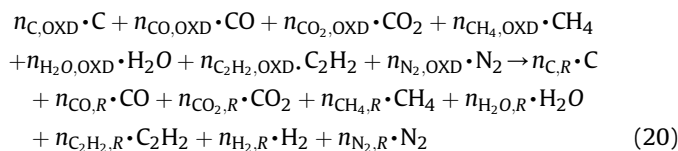


Fig. 2. Overall solution algorithm for a three zone equilibrium and kinetic free model [54].



Reaction stoichiometry:



Constituent balance:

$$ttl_{C,R} = n_{C,OXD} + n_{CO,OXD} + n_{CO_2,OXD} + n_{CH_4,OXD} + 2n_{C_2H_2,OXD} = n_{C,R} + n_{CO,R} + n_{CO_2,R} + n_{CH_4,R} + 2n_{C_2H_2,R}$$
 (21)

$$ttl_{H,R} = 2n_{H_2,OXD} + 2n_{H_2O,OXD} + 4n_{CH_4,OXD} + 2n_{C_2H_2,OXD} = 2n_{H_2,R} + 2n_{H_2O,R} + 4n_{CH_4,R} + 2n_{C_2H_2,R}$$
 (22)

Table 1

Details of biomass with input parameters selected from published literature for model validation [4,50–53]

Material/reference/molecular formula	C/H molar ratio	Equivalence ratio	Moisture content (%)	HHV (MJ/kg)
Peach pits No. 2 [4]	0.640	0.258	10.9	23.179
C <sub>1</sub> H <sub>1.562</sub> O <sub>0.568</sub>				
Peach pits No. 3 [4]	0.640	0.2638	10.9	23.179
C <sub>1</sub> H <sub>1.562</sub> O <sub>0.568</sub>				
Peach pits No. 4 [4]	0.640	0.2673	10.9	23.179
C <sub>1</sub> H <sub>1.562</sub> O <sub>0.568</sub>				
Douglas fir wood blocks [4]	0.697	0.2936	5.4	21.296
C <sub>1</sub> H <sub>1.434</sub> O <sub>0.594</sub>				
Whole log wood chips No. 1 [4]	0.675	0.2764	18	19.976
C <sub>1</sub> H <sub>1.4825</sub> O <sub>0.713</sub>				
Whole log wood chips No. 2 [4]	0.708	0.3322	32	19.976
C <sub>1</sub> H <sub>1.413</sub> O <sub>0.670</sub>				
Whole log wood chips No. 5 [4]	0.708	0.2464	9.80	19.976
C <sub>1</sub> H <sub>1.413</sub> O <sub>0.670</sub>				
Corn cobs 6" choke [4]	0.649	0.2893	11	19.232
C <sub>1</sub> H <sub>1.541</sub> O <sub>0.782</sub>				
Corn cobs 6" choke [4]	0.649	0.2669	11	18.744
C <sub>1</sub> H <sub>1.541</sub> O <sub>0.782</sub>				
Cubed alfalfa seed straw [4]	0.636	0.2600	7.90	18.360
C <sub>1</sub> H <sub>1.572</sub> O <sub>0.781</sub>				
Cubed alfalfa seed straw [4]	0.636	0.245	7.90	18.360
C <sub>1</sub> H <sub>1.572</sub> O <sub>0.781</sub>				
Birch wood [50]	0.678	0.3268	10	18.900
C <sub>1</sub> H <sub>1.476</sub> O <sub>0.73</sub>				
Coir dust [50]	0.781	0.3135	15	19.800
C <sub>1</sub> H <sub>1.281</sub> O <sub>0.605</sub>				
Subabul wood [51]	0.689	0.317	11	20.017
C <sub>1</sub> H <sub>1.451</sub> O <sub>0.697</sub>				
Cubed California cotton gin trash [52]	0.632	0.3016	23.50	20.227
C <sub>1</sub> H <sub>1.582</sub> O <sub>0.689</sub>				
Wood R. No. 98 [53]	0.683	0.323	17.81	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood R. No. 98 [53]	0.683	0.277	11	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 98 [53]	0.683	0.2839	16.52	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 920 [53]	0.683	0.3251	6.01	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 910 [53]	0.683	0.2778	6.99	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 910 [53]	0.683	0.285	17.81	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 929 [53]	0.683	0.2667	7.41	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 1117 [53]	0.683	0.2892	11.26	19.668
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				
Wood chips R. No. 910 [53]	0.683	0.2978	16.52	19.826
C <sub>1</sub> H <sub>1.464</sub> O <sub>0.695</sub>				

$$ttl_{O,R} = n_{CO,OXD} + 2n_{CO_2,OXD} + n_{H_2O,OXD} = n_{CO,R} + 2n_{CO_2,R} + n_{H_2O,R}$$
 (23)

$$ttl_{N,R} = 2n_{N_2,OXD} = 2n_{N_2,R}$$
 (24)

Energy balance:

$$\sum_k n_{K,OXD} [h^0_f + (h_{T,OXD} - h_{298})]_{K,OXD} = \sum_j n_{j,R} [h^0_f + (h_{T,R} - h_{298})]_{j,R} + h_{1,R}$$
 (25)

### 3.4. Solution algorithm

Independent solution of each zone of model is obtained by the method of iteration and coupled with each other to yield an overall

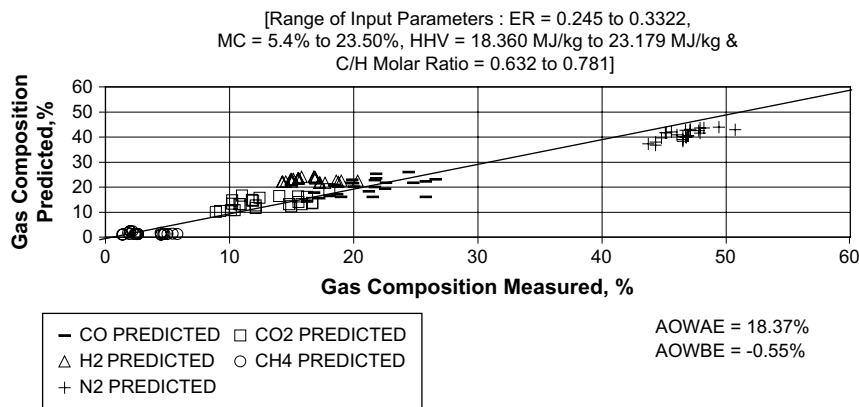


Fig. 3. Model validation with published experimental results of the final gas composition.

solution of the model. Fig. 2 depicts the overall solution algorithm of the model. The first zone is pyrolysis zone. Output of pyrolysis zone model becomes input for oxidation zone model and the output of oxidation zone model becomes input for reduction zone model. The computer program to solve each zone model has been developed in Turbo-C/C++ language and the complete program interlinks all of the three zone solutions for getting the gas compositions, temperature at each zone and gasifier performance parameters.

#### 4. Model validation

To establish utility of the present three zone equilibrium and kinetic free model for the complete range of solid feed stocks and operating conditions, the sufficient numbers (24 different biomass) of published data points have been selected for model validation. The various biomasses with input parameters selected are given in Table 1. In all cases char is modeled as graphitic carbon [2,38,39] balance char in reduction zone is assumed to be zero [38,39] and heat loss is assumed to be 10% of the product of equivalence ratio and HHV [2,41–43].

Figs. 3 and 4 shows the model validation with published experimental results of the final gas composition and LHV (lower heating value) of gas, respectively.  $C_2H_2$  is not compared due to absence of published experimental data. It can be seen from Figs. 3 and 4 that the model predictions are relatively in good agreement with published experimental results as reflected from their error levels. The overall weighted absolute (AOWAE) and bias error (AOWBE) of the model over 24, published experimental data for gas composition is 18.37 and  $-0.55\%$ , respectively, as shown in Fig. 3. The average absolute error (AAE) and average bias error (ABE) for LHV is 7.82 and 1.37%, respectively, as shown in Fig. 4. These results definitely, prove the worthiness of the model looking to the large

numbers of variables involved in the published experimental data. It can therefore be stated that the present model developed with the simplest approach can be used to generate biomass specific performance data, which is needed for reactor design.

#### 5. Model predictions

Main aim of any model lies in its utility as a key for design, scale-up and performance predictions. Accordingly, the present three zone equilibrium and kinetic free model, which has been validated with published experimental results to a sufficient degree of accuracy, has been used to study the influence of equivalence ratio and moisture content on the zone wise gas composition, temperature and gasifier performance parameters. The influence of equivalence ratio and moisture content on zone wise gas composition, temperature and gasifier performance parameters have been studied for Subabul wood as a feed stock, the details of which is presented in Table 2. The salient features of these predictions and observations are presented in the following paragraphs.

##### 5.1. Influence of equivalence ratio (ER)

Table 3 shows the gas composition of the pyrolysis zone. No effect of equivalence ratio has been observed on the gas composition in pyrolysis zone, which is due to the fact that the present model is developed neither considering reaction rates nor considering equilibrium. The pyrolysis zone product and temperature are obtained simply through mass and energy balance with few justifying assumptions. This fact indicates the limitation of this model because pyrolysis is governed by the rate of heating and temperature levels [15–19].

Fig. 5 shows the influence of equivalence ratio on the gas composition of oxidation zone. Increasing  $N_2$  with increasing

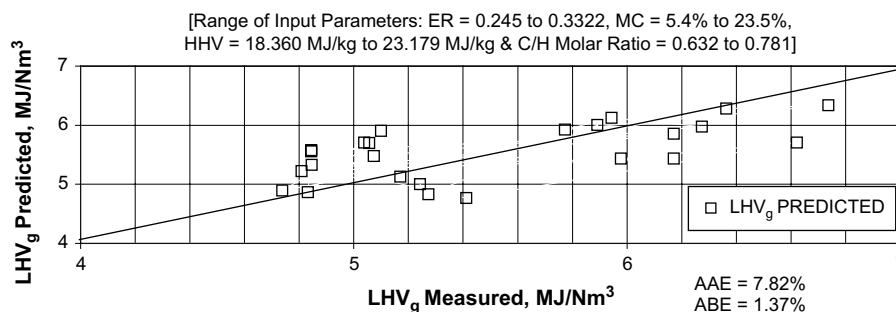


Fig. 4. Model validation with published experimental results of LHV (lower heating value) of gas.



**Table 2**

Range of various parameters selected for model prediction

Biomass Subabul wood	HHV (MJ/kg)	Range of moisture content (%)	Range of equivalence ratio	Heat loss (%)
C <sub>1</sub> H <sub>1.4513</sub> O <sub>0.6986</sub>	19.777	0–38	0.25–0.45	10

equivalence ratio is quite obvious, while CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> and H<sub>2</sub>O are observed to be decreasing. This may be explained on the basis of the fact that CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> and H<sub>2</sub>O generations depends on elemental composition of biomass which is constant for given biomass material and hence the relative compositions will obviously decrease with increasing air intake and equivalence ratio. The CO and CO<sub>2</sub> levels are observed to be increasing with increasing equivalence ratio. This is obviously due to more and more oxidation of char with increasing equivalence ratio. Furthermore, the rate of increase in CO is observed to be higher than that of CO<sub>2</sub>. This may be attributed to the fact that under oxygen deficient atmosphere and the presence of highly reactive char, the partial oxidation of char will be dominant [30,31,44–46].

Fig. 6 depicts the influence of equivalence ratio on the gas composition of reduction zone. The decreasing CO and increasing CO<sub>2</sub> with increasing equivalence ratio is certainly due to oxidation of CO at higher equivalence ratio. The concentration of both these constituents is nearly equal at equivalence ratio of 0.3. This signifies that the gasifier must be operated below this equivalence ratio if one desires to achieve better gas quality. The hydrogen concentration reduces at a slower rate as compared to H<sub>2</sub>O concentration with increasing equivalence ratio. This may be explained by the fact that both these constituents are involved in water–gas shift equilibrium, which consumes CO and H<sub>2</sub>O and produces H<sub>2</sub> and CO<sub>2</sub> [2–4,33–35,39,47]. The CH<sub>4</sub> is observed to be nearly constant due to model assumption.

Fig. 7 shows the influence of equivalence ratio on the temperature at each zone. Temperature of pyrolysis zone is remaining constant with increasing equivalence ratio while temperature of oxidation and reduction zones are increasing with increasing equivalence ratio. The rate of increase of temperature as a function of equivalence ratio is higher in reduction zone as compared to oxidation zone, because the products of the oxidation zone enters at a high temperature in reduction zone plus the amount of char needed for endothermic reduction reactions is reduced, because at higher equivalence ratio most of the char is utilized in oxidation zone (as shown in Fig. 5). This is more clearly observed at equivalence ratio of 0.45 where both oxidation and reduction temperatures become nearly equal [2–4,34,35,39,48,49].

Figs. 8 and 9 presents the variation of gas yield and LHV of gas as a function of equivalence ratio. Obviously, gas yield in oxidation and reduction zones are increasing with increasing moles of air intake

**Table 3**

Gas composition of pyrolysis zone

CO <sub>p</sub> (%)	CO <sub>2,p</sub> (%)	H <sub>2,p</sub> (%)	H <sub>2</sub> O <sub>p</sub> (%)	CH <sub>4,p</sub> (%)	C <sub>2</sub> H <sub>2,p</sub> (%)	C <sub>p</sub> (%)	T <sub>p</sub> (K)
5.94	3.78	8.05	77.26	3.08	1.89	17.18	816.96

while, gas LHV sharply decreases with increase in equivalence ratio, due to oxidation of gas phase constituents [2,4,34,35,39]. LHV of gas is optimum at equivalence ratio in the vicinity of 0.25 for woody biomass where solid carbon conversion is completed [2,3,4,34,41]. Fig. 10 shows the energy efficiency (which is the product of gas yield and gas LHV) of gasifier at reduction zone as a function of equivalence ratio where energy efficiency of gasifier is decreasing with increasing equivalence ratio, which is quite obvious.

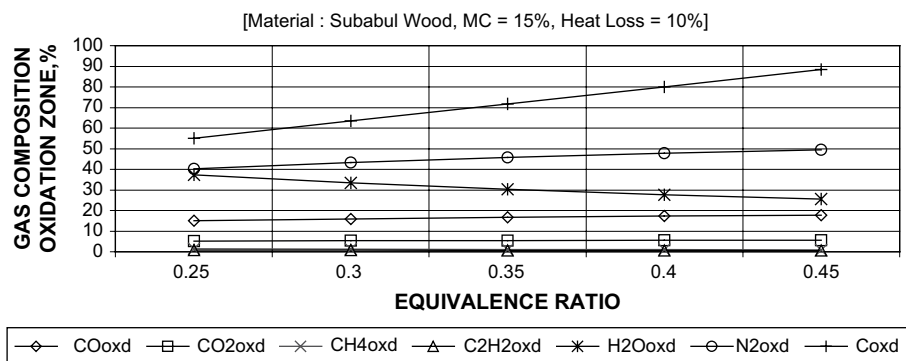
Thus, the overall effect of increasing equivalence ratio is to reduce the level of CO, H<sub>2</sub> and CH<sub>4</sub> and thereby to reduce the gas quality. These observations are quite consistent with the field observations as well as the predictions from the thermodynamic equilibrium and KF models [2–4,39,48,49] and thus once again validate the model qualitatively.

### 5.2. Influence of moisture content (MC)

Figs. 11–17 presents the influence of moisture content on the gas composition, temperature level and gasifier performance parameters at each zone with constant equivalence ratio of 0.3. The heat loss is assumed to be 10% of the product of HHV and equivalence ratio [2,41–43] and the char carry over is assumed to be 0% [38,39].

Figs. 11–13 represents the influence of moisture content on the gas composition at each zone. Fig. 11 shows the gas composition of pyrolysis zone as a function of moisture content. It is observed that all concentrations except H<sub>2</sub>O are decreasing with increasing moles of water vapor, which is quite obvious. Fig. 12 shows the gas composition of oxidation zone as a function of moisture content. It is observed that all concentrations are decreasing with increasing moles of moisture except H<sub>2</sub>O. For the same biomass and constant equivalence ratio, these predictions are quite logical. Fig. 13 shows the influence of moisture content on final gas composition. Once again it is observed that CO, H<sub>2</sub> and CH<sub>4</sub> concentrations are decreasing with increasing moisture content, which is obviously due to increased availability of moles of moisture in the system.

Fig. 14 shows the influence of moisture content on the temperature at each zone. Decreasing trends of temperature at each zone as a function of moisture content is quite reasonable because higher moisture content consumes more amount of heat energy as a latent and sensible heat and thereby reduces the temperature levels [2,3,39,47].

**Fig. 5.** Influence of equivalence ratio (ER) on gas composition of the oxidation zone.

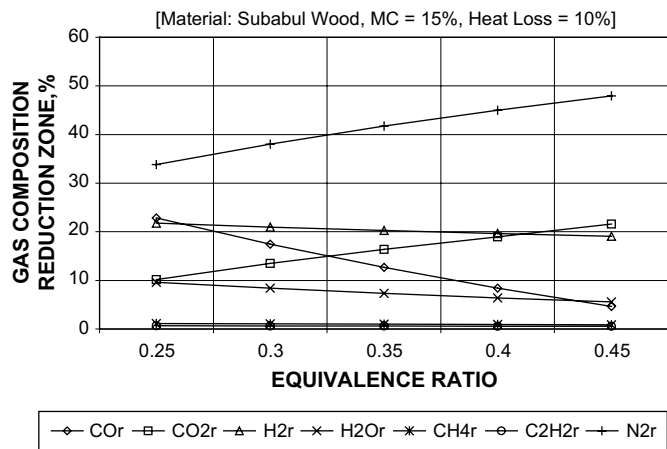


Fig. 6. Influence of equivalence ratio on gas composition of the reduction zone.

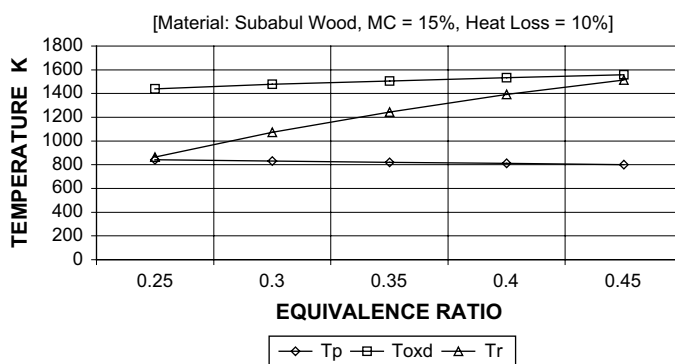


Fig. 7. Influence of equivalence ratio on temperature level at each zone.

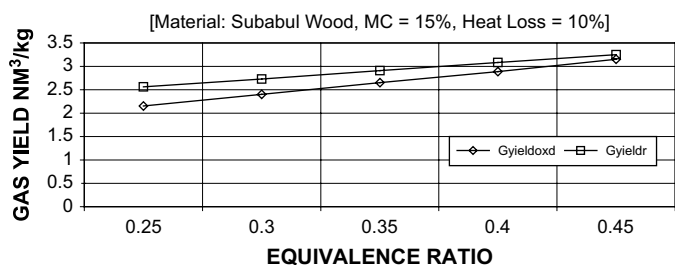


Fig. 8. Influence of equivalence ratio on gas yield of oxidation and reduction zones.

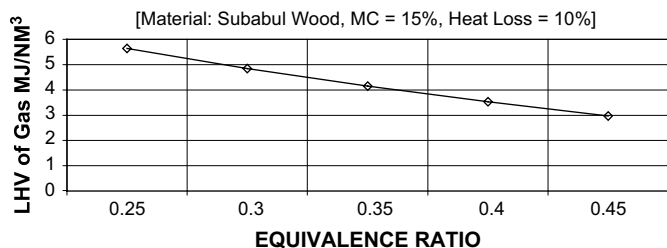


Fig. 9. Influence of equivalence ratio on LHV of gas.

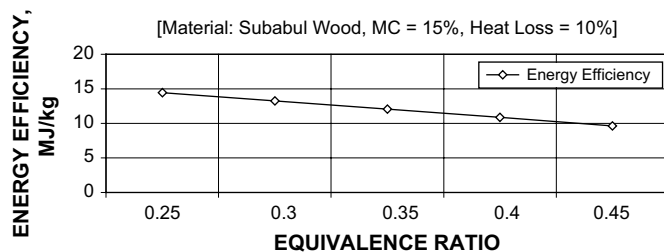


Fig. 10. Influence of equivalence ratio on energy efficiency of the gasifier (reduction zone).

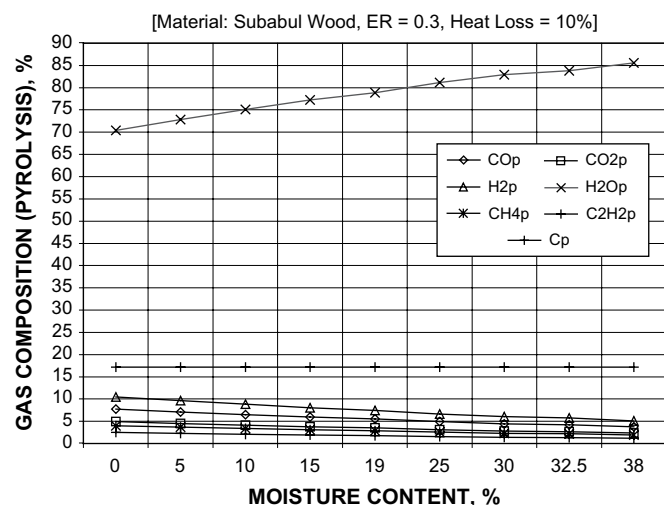


Fig. 11. Influence of moisture content (MC) on gas composition of the pyrolysis zone.

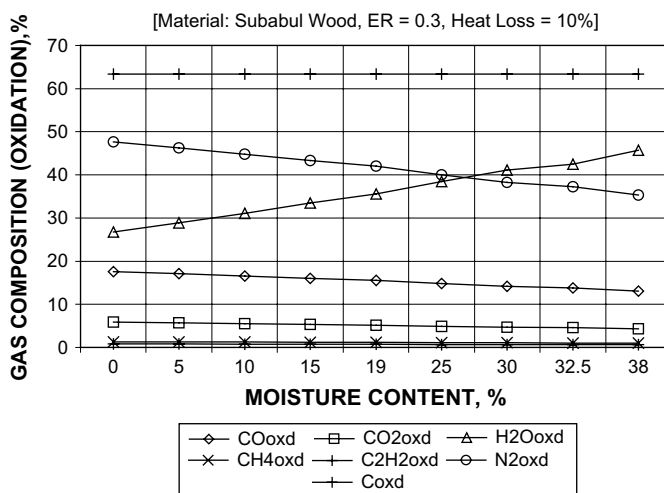


Fig. 12. Influence of moisture content on gas composition of the oxidation zone.

Figs. 15–17 represents the variations of gas yield, LHV of gas and energy efficiency (i.e., the product of gas yield and gas LHV) of the gasifier as a function of gas content, respectively. Increasing gas yield and decreasing the trend of LHV with increase in moisture can easily be linked with the increased availability of moles of moisture in the system [2,4,39,47]. The overall energy efficiency at reduction zone does not show significant variation with increasing

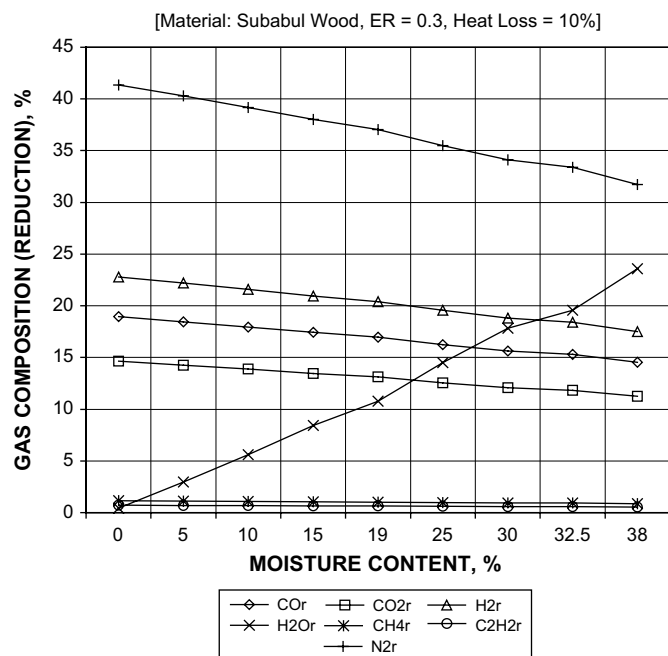


Fig. 13. Influence of moisture content on gas composition of the reduction zone.

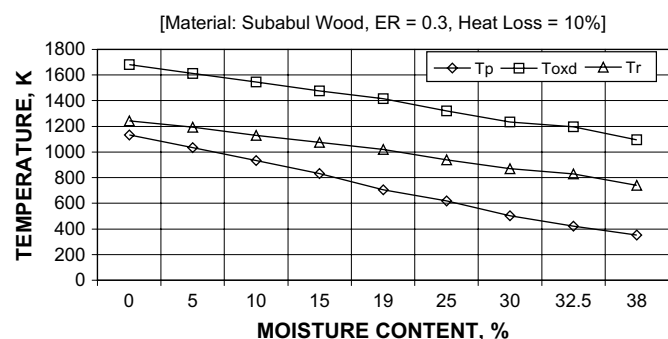


Fig. 14. Influence of moisture content on the temperature level at each zone.

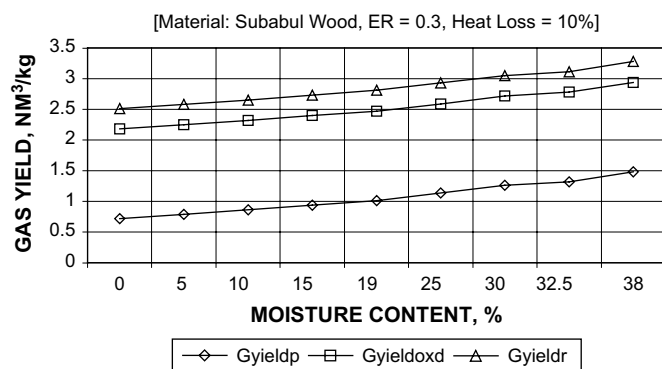


Fig. 15. Influence of moisture content on the gas yield at each zone.

moisture content because it is simply the product of gas yield and gas LHV. Yield of gas increases while LHV of gas decreases and hence energy efficiency of gasifier does not show significant variations. However, it must be noted that at very high levels of

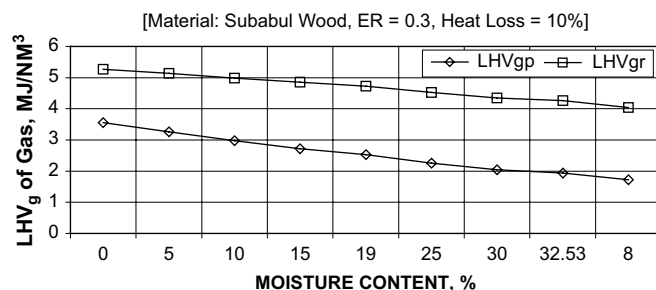


Fig. 16. Influence of moisture content on LHV of gas at pyrolysis and reduction zones.

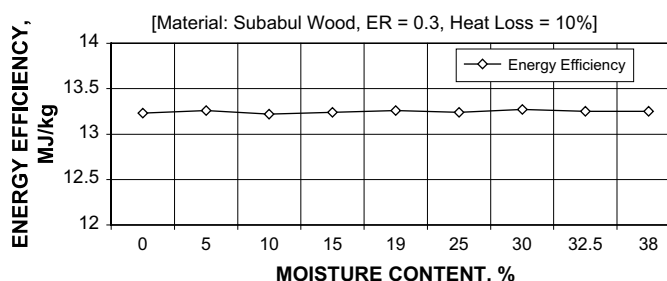


Fig. 17. Influence of moisture content on energy efficiency of the gasifier (reduction zone).

moisture, reaction temperatures may not be favorable which will result in much inferior gas quality and hence efficiency. Thus it may be stated that the model very logically handles the predictions of gas composition and temperature levels in each zone as a function of moisture content, too.

## 6. Conclusions

Based on the formulation of the three zone equilibrium and kinetic free model of biomass gasifier, validation and the predictions of the following conclusions may be derived.

- (1) The comparison of the model predictions with published experimental results and illustrated closeness between the two within  $\pm 20\%$  proves the quantitative and qualitative validity of the present three zone equilibrium and kinetic free model for most parameters of interest.
- (2) The present three zone equilibrium and kinetic free model is the simplest and offers a novel approach of modeling the gasifier. This model clearly provides the operating range of equivalence ratio and moisture content for the woody biomass materials. Furthermore, this model facilitates the prediction of maximum temperature in oxidation zone of gasifier, which provides useful information for the design of gasifier and the selection of material for the construction.
- (3) The merits of the model lies in the fact that it is capable of handling predictions for all category of biomass materials with wide operating range of equivalence ratio and moisture content in all the three principal zones of gasifier.

## References

- [1] Ratnadhariya JK, Channiwala SA. Two zone equilibrium and kinetic free modeling of gasifier. Proceedings of the 12th European Conference and Technical Exhibition on Biomass for Energy, Industry and Climate Protection. Amsterdam, The Netherlands; 2002. p. 813–816.



- [2] Channiwalla SA. On biomass gasification process and technology development – some analytical and experimental investigations. Ph. D thesis, Indian Institute of Technology, Bombay, India; 1992.
- [3] Gumz W. Gas producers and blast furnaces – theory and method of calculation. New York: John Wiley; 1950. p. 109–167.
- [4] Jenkins BM. Downdraft gasification characteristics of major California residue derived fuels. Ph.D. thesis, University of California; 1980.
- [5] Storm C, Rudiger H, Spliethoff H, Hein KRG. Co-pyrolysis of coal/biomass and coal/sewage sludge mixtures. *J Eng Gas Turbines Power* 1999;121: 55–3.
- [6] Mastral FJ, Esperanza E, Berrueto C, Serrano S, Ceamanos J. Co-pyrolysis and co-gasification of polyethylene and sawdust mixtures in a fluidised bed reactor, temperature influence. *Proceeding of the 12th European Conference and Technical Exhibition on Biomass for Energy, Industry and Climate Protection*. Amsterdam, The Netherlands; 2002. p. 636–639.
- [7] Berends R, Brem G. Two-stage gasification of biomass for the production of syngas. *Proceeding of the 12th European Conference and Technical Exhibition on Biomass for Energy, Industry and Climate Protection*. Amsterdam, The Netherlands; 2002. p. 622–624.
- [8] Van de Steene L, Salvador S, Napoli A. Rice husk, straw and bark behaviour during pyrolysis, combustion and gasification fundamental study. *Proceeding of the 12th European Conference and Technical Exhibition on Biomass for Energy, Industry and Climate Protection*. Amsterdam, The Netherlands; 2002. p. 821–826.
- [9] Antal MJ. Biomass pyrolysis: a review of the literature, Part I & II. New York: Advances in Solar Energy Society; 1983.
- [10] Antal MJ, Plett EG, Chung TP, Summerfield M. Recent progress in kinetic models for coal pyrolysis. *ACS Div; Fuel Chem* 1977;22(1):137.
- [11] Shafizadeh F. Introduction to pyrolysis of biomass. *J Anal Appl Pyrolysis* 1982;3:283–305.
- [12] Deglise X, Magne P. Pyrolysis and industrial charcoal. In: Hall DO, Overend RP, editors. Biomass – renewable energy. New York: John Wiley; 1987. p. 221–35.
- [13] Parikh, J, Ghosal G, Channiwalla SA. A critical review on biomass pyrolysis. *Proceeding of the 12th European Conference and Tech. Exhibition on Biomass for Energy, Industry and Climate Protection*. Amsterdam, The Netherlands; 2002. p. 889–892.
- [14] Channiwalla SA, Parikh PP. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. *J Fuel* 2002;81:1051–63.
- [15] Selvig WA, Gibson IH. Calorific value of coal. In: Lowry HH, editor. Chemistry of coal utilization, vol. 1. New York: Wiley; 1945. p. 139.
- [16] Strache H, Lant, R. Kohlenchemie, Akademische Verlagsgesellschaft. Leipzig; 1924. p. 476.
- [17] Steuer W. Brennstoff-Chem 1926;7:344–7.
- [18] Sumegi L. Magyar Mernok Eleteszgyelet Kozlonye 1939;73:345–6. *Chem Abs* 1940;34:1459.
- [19] Vondreck R. Brennstoff-Chem 1927;8:22–3.
- [20] Milne TA. Pyrolysis – the behaviour of biomass below 600 °C. In: Reed TB, editor. Biomass gasification – principles and technology. NJ: Noyes Data Corporation; 1981. p. 91–111.
- [21] Antony DB, Howard JB. Coal devolatilization and hydrogasification. *J AIChE* 1976;22:625.
- [22] Mott RA, Spooner CE. *Fuel* 1940;19: 226–1, 242–251.
- [23] Reed TB, Levie B. A simplified model of the stratified downdraft gasifier. *International Bio-energy Directory Handbook* 1984:379–89.
- [24] Amundson NR, Arri LE. Char gasification in a counter current reactor. *J AIChE* 1978;24(1):87–100.
- [25] Srinivas B, Amundson NR. A single particle char gasification model. *J AIChE* 1980;26(3): 487–6.
- [26] Cho YS, Joseph B. Heterogeneous model for moving-bed coal gasification reactors. *Ind Eng Chem Process Des* 1981;20(2):314–8.
- [27] Thring MW. The science of flames and furnaces. 2nd ed. London: Chapman and Hall; 1962.
- [28] Cardiner WC. Combustion chemistry. NY: Springer Verlag; 1984.
- [29] Lewis B, Von Guertner E. Combustion flames and explosion of gases. 3rd ed. New York: Academic Press; 1987.
- [30] Evans D, Emmons H. Combustion of wood charcoal. *Fire Res* 1977;1:51–6.
- [31] Bhagat PM. Wood charcoal combustion and the effects of water application. *Combust Flame* 1980;37:275–91.
- [32] Buckens AG, Schoeters JG. Mathematical modeling in gasification. In: Bridgewater AV, editor. Thermochemical processing of biomass. London: Butterworths; 1984. p. 177–200.
- [33] Chern SM, Walawander WP, Fan LT. Equilibrium modeling of a downdraft gasifier. *Chem Eng Comm* 1991;108:243–65.
- [34] Ali TR. Studies of biomass gasification. Ph.D. thesis, Univ. of California, Berkeley; 1982.
- [35] Susanto H. Moving bed gasifier with internal recycle and separate combustion of pyrolysis gas, Ph.D thesis. Institute of Technology, Bandung; Indonesia, 1984.
- [36] Kersten SRA, Prins W, Vander Drift A, Van Swaaij. Interpretation of biomass gasification by quasi-equilibrium models. *Proceeding of the 12th European Conference and Technical Exhibition on Biomass for Energy, Industry and Climate Protection*, Amsterdam, The Netherlands; 2002. p. 772–6.
- [37] Reed TB, Levie E. A mathematical model for stratified downdraft gasifiers. *ACS, Div Fuel Chem* 1983;28(5):410–20.
- [38] Gordan S, McBride BJ. Computer program for calculations of complex chemical equilibrium compositions – rocket performance, incident and reflected shocks and Chapman-Jouguet detonation. NASA 1971. Report No. 273.
- [39] Desrosiers R. Thermodynamics of gas-char reaction. In: Reed TB, editor. Biomass gasification – principles and technology. NJ: Noyes Data Corporation; 1984. p. 119–53.
- [40] Ratnadhariya JK. Kinetic free modeling of biomass gasifier – a first step towards the analysis of biomass integrated gasifier/steam injected gas turbine (BIG/STIG) system. M.E dissertation, SVRCET, Surat, India; 1998.
- [41] Shand RN, Bridgewater AV. Fuel gas from biomass: status and new modeling approaches. In: Bridgewater AV, editor. Thermochemical processing of biomass. London: Butterworths; 1984. p. 229–54.
- [42] Parikh PP. State of the art report on gasification of biomass. Interim Report of DNES (201/20/84 BM) Project, Ministry of Energy, Govt. of India 1984.
- [43] Blik A. Mathematical modeling of a co-current fixed bed coal gasifier, Ph. D thesis, Twente University of Technology, Eindhoven, The Netherlands; 1984.
- [44] Rossberg MZZ. *Elektrochem* 1956;60:952–6.
- [45] Kontinen J, Kallio S, Kilpinen P. Oxidation of a single char particle extension of the model and re-estimation of kinetic rate constants. *Combustion and Materials Chemistry*. Finland: Biskopsgatan 8, Abo Akademi University Abo; 2002.
- [46] Arthur JR. Reaction between carbon & oxygen. *Trans. Faraday Soc* 1951;47:164–78.
- [47] Schalpf P, Tobler J. Theoretische und praktische untersuchungen über den betrieb von motorfahrzeugen mit hohgas. Switzerland: Bern: Schweizerische Gesellschaft Fur das Studium der Motorbrennstoffe; 1937.
- [48] Denn MM, Wen CY. Parameter sensitivity and kinetic free modeling of moving bed coal gasifiers. *Ind Eng Chem Fundam* 1979;18(3):286–8.
- [49] Kosky PG, Floess JK. Global model of counter current coal gasifier. *Ind Eng Chem Process Des* 1980;19: 586–2.
- [50] Liinanki L, Svenningsson P, Thessen G. Gasification of agricultural residues in a down draft gasifier. In: Coombs PW, Hall DO, editors. 3rd E.C. Conference on Energy from Biomass. England: Elsevier; 1985. p. 832–836.
- [51] Shashikantha. Performance evolution of gasifier – Engine system operating on dual fuel mode. Bombay, India: M Tech dissertation, Indian Institute of Technology; 1988.
- [52] Hodam RH, Williams RO. Small scale gasification of biomass to produce a low Btu gas. In: Washington DC, editor. Symposium on energy from biomass and wastes, IGT; 1978. p. 729–748.
- [53] Walawander WP, Chern SM, Fan LT. Wood chip gasification in a commercial downdraft gasifier. In: Overend RP, Milne TA, Mudge LK, editors. Fundamentals of thermo-chemical biomass conversion. NY: Elsevier; 1985. p. 911–21.
- [54] Stull DR, Prophet H. JANAF thermochemical tables. 2nd ed. Washington: NSRDS-NBS-37; 1971.